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Technical Report

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BENCHMARKING OF THE STATE-OF-THE-ART IN
NONDESTRUCTIVE TESTING/EVALUATION FOR
APPLICABILITY IN THE COMPOSITE ARMORED
VEHICLE (CAV) ADVANCED TECHNOLOGY
DEMONSTRATOR (ATD) PROGRAM

DLA900-90-D-0123

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11. SUPPLEMENTARY NOTES The benchmarking study was extended to include a more detailed assessment of selected NDE methods. NDE methods to be evaluated include Microwave, IR Thermography, Eddy Current, Reverse Geometry X-ray, Large Area 2-D Array UT, and Shearography.

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13. ABSTRACT *(Maximum 200 words)* This technology assessment report is the result of compilation, review, and assessment of information and data concerning the development and use of NDE/T as applied to advanced composites that may be used in the CAV ATD Program. This information has been gained from both published literature and as well as work in progress. It includes the results of a detailed bibliographic search using all the data bases held within the Defense Technical Information Center, supplemented where ever possible by other data bases. In addition, direct contacts and academic, industrial, and government research and development centers and applications laboratories were made.

Discussions and recommendations contained in this report focus on the current state-of-the-art of composite NDE/T technologies and their capabilities and limitations for both the classical post process and real-time in-process inspection techniques. Furthermore, this effort includes an assessment of future developments and research trends including a projected time line.

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1. INTRODUCTION

At the request of the U. S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC), NTIAC was requested to conduct a technology assessment of the current and emerging state-of-the-art in areas of nondestructive evaluation/testing (NDE/T) which might be applied to composite materials.

TARDEC is currently involved in advancing a Composite Armored Vehicle (CAV) Advanced Technology Demonstrator (ATD). The objective of the program is to develop a light-weight, highly survivable, and deployable vehicle that maximizes the use of polymer composites. In order for CAV to be successful, it was considered that the necessary enabling technologies must be in place prior to commitment to a full scale development and production of composite hull and turret structures. The results of this technology assessment provide timely support to both design development and demonstrator fabrication in identifying NDE/T techniques best suited for the type of structures being considered.

This technology assessment report is the result of compilation, review, and assessment of information and data concerning the development and use of NDE/T as applied to advanced composites that may be used in the CAV ATD Program. This information has been gained from both published literature and as well as work in progress. It includes the results of a detailed bibliographic search using all of the data bases held within the Defense Technical Information Center, supplemented where ever possible by other data bases. In addition, direct contacts with academic, industrial, and government research and development centers and applications laboratories were made.

Discussions and recommendations contained in this report focus on the current state-of-the-art of composite NDE/T technologies and their capabilities and limitations for both the classical post process and real-time in-process inspection techniques. Furthermore, this effort includes an assessment of future developments and research trends including a projected time line.

2. MATERIALS AND MANUFACTURING METHOD CONSIDERATION WITH REGARD TO NONDESTRUCTIVE EVALUATION

The use of composite materials is extensive. Since early military applications generated during World War II, DoD use has grown immensely. Successful composite use has generated an ever increasing demand for advanced applications. A large fraction of advanced weapon system components and assemblies now contain composite materials. Private industry has advanced into large scale commercial applications in aerospace, automotive, boating and sports.

Modern technology requires materials with unusual combinations of properties that cannot be met by conventional metal alloys, ceramics, and polymeric materials. Engineers are increasingly searching for structural materials that are stiff, have high strength and low density, are impact and abrasion resistant, and are not easily corroded. Modern composite materials often satisfy many, if not all, of these criteria.

A composite material may be broadly defined as one or more discontinuous phases embedded in a continuous phase. The discontinuous phase is much harder and stronger than the continuous phase and is called the reinforcement or reinforcing material. The continuous phase is most often referred to as the matrix. This combination can provide properties not possessed by either of the individual constituents.

The success of composites is derived from the outstanding strength-to-weight ratio, resistance to corrosion, and relative ease of manufacture. Perhaps the most unique characteristic that distinguishes composites from other materials is that the manufacture of a given composite structure and the synthesis of the material most often occur simultaneously. Furthermore, the resulting composite component can be manufactured to near net shape.

The accumulation of defects (and damage) in a composite is closely tied to the strength, life, and stiffness of the structure. Knowledge of defects (and damage) is of primary importance in composite use. Various defects, which adversely influence the service life of the composite, can be introduced during manufacture. Additionally, the material can accumulate flaws and defects during in-service use. These include fatigue damage, impact damage, and environmental degradation.

To determine the performance and serviceability of a composite structural component, it is necessary to use nondestructive evaluation/testing methods. NDE/T results must be able to ensure the safety of the structural composite both before <u>and</u> during service. It follows then that this effort should be made "cradle to grave"; it should continue from the time of manufacture and throughout the life cycle of the component.

In an ideal situation, determining appropriate NDE/T methods and material acceptance criteria for composite structure go hand in hand. To achieve these goals the following approach is recommended:

Obtain necessary data on composite components and parts such as type of material, structure configurations, dimensions, and preliminary requirements for NDE including type of possible defects (delaminations, voids, disbonds, etc.), desirable minimum acceptance defect size, permissible type of coupling NDE sensors with composite material (dry contact, liquid contact, non-contact, etc.).

Select several representative types of composite materials and design samples with built-in defects and parameters previously determined. The sizes of defects should be equal, greater and smaller than initially identified acceptable sizes.

Based on information obtained, the appropriate non-destructive methods for detecting defects and their evaluation should be developed. Such techniques are to be evaluated as to their appropriateness, cost effectiveness, reliability, and rapidity.

After applying selected and/or developed NDE techniques to the fabricated samples, the thermal cycling and proof-load tests of the samples are to be conducted. The samples that have passed proof-load tests are to be re-examined by the NDE techniques and using the same inspection parameters established in pre-proof-load examinations. All of the data obtained from NDE, thermal cycling, and proof-load tests are to be analyzed, and as a result of these efforts accept/ reject criteria for a particular composite part or component should be selected.

Selection of appropriate NDE techniques requires a detailed understanding of the design, composition, and methods of manufacture of the materials and structure to be inspected. Limited background information was available for use in this technology assessment. The following details and guidelines were provided:

a) consider fiber reinforced composite materials, most likely laminate in nature; manufacturing methods may include resin transfer molding, multilaminate layup, pultrusion, etc.

b) material thickness to fall in the 1/2 inch to 2 inch range

c) reinforcing fibers may be non-conducting (glass) or conducting (graphite/epoxy) but advanced composites such as metal matrix, ceramics, carbon-carbon, etc. will probably not be used.

d) focus should be only on the CAV hull structure, do not consider armor

e) do not consider multi-layer structures (integrated hull/armor, low observable materials, signature control materials)

The information above is appropriate to perform a general review of all NDE technologies, however, it is not in sufficient detail to make specific NDE recommendations. Whenever details on the engineering design and actual composite materials to be used in the CAV are available, the information contained in this technology assessment can be used to help define and develop those recommendations

No single NDE technique stands out as a total solution. Each has its own strengths and shortcomings depending on the type of material being investigated and type of flaw or defect being sought out. Appendix B contains information on the various NDE technologies used for composite inspection. More detail for individual methods is given in Section 5.

Most NDE professionals will agree that the ideal approach is to employ a variety of complementary techniques. However, in some cases, this degree of flexibility is over balanced by budgetary constraints. Any one or combination of NDE techniques should be fast, reliable, easy to use, and economical.

3. TYPES OF DEFECTS TO BE STUDIED

The types of flaws to be detected in composite structures is wide-ranging. They include (but are not restricted to):

- Voids
- Porosity
- Cracks
- Inclusions
- Improper cure state
- Disbonds at joined surfaces
- Incursion of water and/or other liquids
- Integrity of metal and/or other structures embedded into or bonded onto structure
- Broken weave/filaments
- Warped weave/filaments
- Delamination
- Damage

The increased use of thick composites presents quite a challenge to non-destructive testing. These materials exhibit a degree of anisotropy that is orders of magnitude above that of previously employed structural materials (such as metals). This anisotropy stems not only from the basic construction of the composite (oriented fibers imbedded within a matrix or open cell structure within honeycomb are only two examples), but it also arises from what are considered "acceptable flaws or defects" within the material. These are found in varying degrees of delamination, porosity, matrix cracking, changing fiber size, broken fibers, etc.

Nondestructive evaluation is intended to reveal <u>both</u> manufactured-in and in-service flaws, defects and damage. Successful nondestructive evaluation requires a methodology where it is possible to distinguish the signals from the "acceptable flaws" from those determined to be unacceptable.

Determination and characterization of unacceptable defects (critical flaws) is often difficult but it is a necessary step towards determining the correct NDE method and equipment. It is most important to understand the size and shape of critical flaws and their location in the composite structure. The types of materials used, how the structure is engineered, service conditions, as well as the size, shape, and location of all varieties of flaws play important roles in determining and defining critical flaws. Critical flaw definition and characterization is often accomplished only after extensive finite element analyses, application of fracture mechanics and failure analysis, and destructive material testing, associated with nondestructive testing.

As described in Section 2, much more definition of the effects of defects is required before appropriate NDE systems can be selected. Production parts must be inspected using some kind of accept-reject criteria, and these criteria must be realistic. A great deal of work is required to establish the relationship between the frequency and/or severity of defects (for example, interply porosity, delaminations, voids, foreign inclusions, broken fibers, resin rich or poor volumes, etc.)and their effects on the strength and durability of composite structural materials.

NDE equipment of all types that might be used with composites is available in a wide range of performance capabilities. With the possible exception of capital equipment costs, the primary considerations when selecting a NDE technology or equipment are related to system sensitivity (what magnitude of defect effect can be or needs to be detected), spatial resolution (what size of defect can be detected), and inspection speed (how long does it take to perform an inspection). Obviously these and many other factors must be considered when selecting equipment. However, one fact remains constant: it is not cost effective to specify equipment with a greater sensitivity and resolution than those related to detecting flaws, defects, and damage equal to or larger than critical flaws.

NDE can be expensive, however, a properly designed and managed NDE program can realize substantial savings by promoting waste minimization, increased throughput, and improved quality of the finished product.

4. NDE/T APPLICATIONS

One consideration of highest importance is that of concurrent engineering; the engineering approach should be one of designing for nondestructive testability. In the context of this report this means that nondestructive evaluation should be considered from the very beginning and throughout the concept and design process, to ensure that it can be successfully employed, both during fabrication and in-service. The importance of nondestructive evaluation is well understood; the ability of achieving it will be greatly simplified if NDE functions are held to the same high priorities as other engineering standards.

As important as building NDE into the program from the beginning, the question of where and when nondestructive evaluation is applied is also very important. It was mentioned above that nondestructive evaluation should be a cradle to grave function. It is important to note here that the role that NDE is playing in manufacturing and fabrication is changing.

In the past, NDE has played a traditional role primarily as a quality control function. In simple terms this has meant that inspection is done at the completion of the fabrication of parts and assemblies, after all of the manufacturing value has been added. This is usually called <u>end of process inspection</u>. Obviously, when the quality of the tested object does not meet standards, it must be rejected. The rejected object may represent a very large investment in time and material. There is some possibility that defects and flaws may be reduced or eliminated through re-work, in a hope that an acceptable part results. Often times this is not possible and the part is scrapped. Both re-work and scrap represent an unnecessary waste of time and resources.

A far better approach, and one that is becoming more widely adopted, is to inspect the parts during the various steps of the manufacturing process. This is known as <u>in-process inspection</u>. Often the same NDE technology used in end of process is used; often no new or exotic equipment is required. In some cases the NDE signals are used by the equipment operator to ensure that the fabrication process is proceeding correctly. The end result of this advanced effort is that waste associated with re-work and scrap is significantly reduced and production efficiency is greatly increased.

The most advanced approach is known as <u>in-process control</u>. This is NDE application in the most advanced form. Here, using the same types of NDE technology described above, the NDE sensor signals are used to control the manufacturing process. The control is performed in real-time so that, in principle, only perfect parts are produced. In-process control systems require a computer in addition to a variety of NDE sensors. These systems are currently being developed, using some off-the-shelf components, with very successful results in reduction of waste and re-work. The potential return on investment of developing NDE sensor in-process control is very attractive.

5. NDE/T TECHNOLOGIES

The following comments on individual nondestructive evaluation methods pertain to inspection of most composite types regardless of the material thickness. At the conclusion of each brief description, a statement is made concerning the relative development of the methodologies as related to their application to the CAV ATD program. These are ranked as:

> Mature technologies are normally available as of-the-shelf components and/or systems and can be used directly or with limited modifications with the CAV ACD.
>
> Developing technologies have been proven in the laboratory and tc some degree in limited applications; they would normally require additional effort for CAV ATD applications.
>
> Laboratory methods are represented by emerging technologies, those that show promise but require a much greater effort for application in the CAV ATD program.

Acoustic Emission

Acoustic emission (AE) testing involves the detection of energy that is spontaneously released by materials when they undergo deformation. For example, when a piece of wood is stressed, audible cracking noise can be detected just before the wood breaks. This same phenomenon occurs in other materials, including composites.

This method requires the monitoring of the material for spontaneous noise generated under load. The detected signals are often in the ultrasonic region rather than in the audible range. It is capable of detecting and characterizing matrix cracking, delamination, and fiber breakage.

One application where acoustic emission testing has found acceptance is in the detection of moisture in honeycomb assemblies. If a honeycomb assembly containing water is locally heated in the vicinity of the water, the increased vapor pressure will force the water to move through the leakage path creating a noise that is measurable with acoustic emission detectors.

This is a mature technology and may be used directly, or with very little modification, in the CAV Program. It may be used in either the end of process or in-process inspection mode.

Acousto-Ultrasonics

The acousto-ultrasonic (also known as the stress wave factor) test method uses an ultrasonic transducer to introduce a specially formulated acoustic pulse into the material under test. The wave form of the pulse is monitored a fixed distance away from the source. Flaws or damage in the material will affect the manner in which the sonic stress wave is transmitted through the material.

The stress wave will be affected most by discontinuities that impede the motion of the stress wave through the material. Although the method is generally used with both transducers on the same side of the part, it may also be used in a through-transmission mode. It is sensitive to delaminations, fiber breakage, matrix cracking, and material porosity inhomogeneities.

This is technology is mature, however, additional efforts would have to be made for specific applications in the CAV ATD program. It can be used in either the end of process or in-process inspection mode.

Eddy Current Testing

Eddy current methods rely on the principles of magnetic induction. Current loops, or eddy currents, are induced in a conducting material by an applied varying magnetic field.

Material electrical conductivity is essential in eddy current testing. In the case of composite materials, this is usually found only in carbon fiber bearing composites. In this type of material eddy currents can be used to monitor fiber orientation and fiber breakage, either from manufactured in or impact damage. Eddy current methodologies have been investigated for years, but this technique has not received a great deal of attention for production or in-service inspection of composites to date.

This technology is in the laboratory category for composites. It is expected to take several years (1 to 3 years) of effort for full maturity.

Infrared Thermography

Infrared (IR) or thermal imaging has been used for some time. Based on the study of how heat energy flows within an object or assembly, this method has been used for energy management as well as nondestructive testing. Thermal imaging systems are now being used for the inspection of composites.

Thermal patterns can be produced by heating the inspect' n surface and monitoring the surface temperature distribution for relative hot spots caused by blockage of the thermal flow away from the surface. The blockage is associated with flaws near the surface; the sensitivity decreases rapidly with flaw depth. One

application is with impact damage, which often results in component damage near the surface of a composite structure. The thermal image can also be produced by heating the far side of the object while monitoring the opposite surface for cold spots where heat flow is impeded by flaws. This through-transmission approach improves the depth sensitivity, however, the method is still more sensitive to near-side flaws.

Thermal imaging has suffered from the lack of a suitable, reproducible methods for producing a thermal gradient in a composite structure. Progress is being made in the development of new thermal imaging systems with greater sensitivity and vastly improved signal analysis tools.

This is a mature technology, however, some effort is required for use specific to the CAV program. It may be used in all modes of process inspection and control.

Laser Holographic Interferometry and Shearography

A hologram (or holograph) is an interference pattern that can be used to study extremely small variations in surface topography of an inspected object. The hologram is formed by the superposition of two wave fronts, an object beam and a reference beam, on a suitable recording material such as a photographic film. An observer looking through the developed hologram sees a virtual image of the inspected object.

When the real object undergoes a small displacement over part of the surface, as a result of stressing by thermal or mechanical means, a variation in the relative phase of the wave fronts will produce an observable fringe pattern, related to the displacement.

Laser interferometric holography techniques were evaluated for composites over 30 years ago. Since that time the major problem in applying this technique has been that of vibrations brought about by working in a production or in-service environment. The inspection approach is very sensitive to extremely small amounts of relative motion in the part surface. The development of phase -locked loop holographic systems has helped mitigate the vibration problems. Furthermore, modern digital signal processing techniques, allowing rapid data acquisition, have also helped.

Shearography, like holography uses an interference pattern to assist in locating flaws. In this method, no separate reference beam is employed. Rather, the returning object beam is doubly imaged, with one of the images slightly shifted or "sheared" relative to the unshifted image. The resulting interference pattern does not reveal bulk surface motion, but only the degree of differential motion of the surface along the direction of the shearing. This makes shearography particularly well suited to many production and depot environments because of the relative immunity to vibration problems.

Flaws located near or on the surface may be indicated with holography and shearography. These techniques are especially sensitive to near surface delaminations and disbonds.

These are mature technologies requiring little modification for CAV application. They may be used in all aspects of process inspection and control.

Liquid Penetrant Testing

Liquid penetrant relies on the ability of a liquid to penetrate into surface flaws. Following application of the special penetrant to the surface, the excess is removed, leaving only that material that has flowed into and been caught in surface cracks, holes, and crevices. Several enhancing methods, including ultraviolet light fluorescence, are used to more easily observe flaw indications.

As this method is limited to surface examination, it has very restricted application to thick section composite materials.

This is a mature technology. It is typically used as a end of process or in-process inspection tool.

Microwave NDE

Microwave techniques function in a way similar to those of radiography. In most applications, a beam of microwave energy strikes the surface of the object to be inspected. Flaws and defects are found through the differential absorption and/or scattering of this energy. Both through-transmission (transmitter and receiver on opposite sides) and backscatter (access to only one side) geometry's are used. Non-conducting composites are best suited for microwave inspection methods.

Nondestructive evaluation based on microwaves has been neglected for many years, primarily on the grounds that microwaves have wavelengths that are too long for meaningful resolution and because microwave measurements are too noisy. New equipment, especially in the millimeter wave domain, now produce accurate and meaningful measurements that may be directly applicable to sandwich composite structures.

In principal, microwave techniques can detect many of the same defects and flaws found when using radiographic and/or ultrasonic methods. Because of the renewed interest in modern microwave technology, it is too early to completely define when and how microwaves may be used in the future.

This is a laboratory technology. It is expected to take several years of effort (2 to 5 years) for full maturity. When fully developed, it could be used in all phases of process inspection and control.

Radiography/Radioscopy

Radiographic or radioscopic imaging relies on the differential absorption and/or scattering of the energetic particles (electromagnetic waves such as x-rays/gamma rays or nuclear particles such as neutrons) as they pass through the material. Flaws or defects that allow more particles to pass or that absorb or scatter the particles can be imaged. Radiography is normally related to images on film whereas radioscopy is most often associated with a video image, often produced from digital data. The most common examples of radiography experienced by most people are chest and dental x-ray radiographs.

X-rays

X-ray radiography inspection systems are typically sensitive to material changes which result in about 1% to 2 % variation in the material thickness or density. Most x-ray inspection systems use film as the detector/imager. State-of-the -art radioscopy systems provide images in real-time with a variety of computer based image enhancement tools. These systems have achieved sensitivities of better than 0.2% in thickness or density variations.

Composite flaws tend to lie between laminates and present very small apparent thickness change. However, the low density of these materials permits the use of low energy x-rays, which helps to enhance the sensitivity. X-rays can also be used to detect porosity and matrix cracks as well as some types of foreign material inclusions.

Reinforcing fibers are difficult to image, making impact damage to composites hard to detect. X-ray radiography is particularly useful for the assessment of honeycomb core defects in bonded sandwich assemblies. The low density and thin composite skins usually provide minimal interference so that the x-rays can produce high quality images. Defects such as crushed core; condensed ply wraps; fatigued, corroded, or cut plies; and foaming adhesive voids can be detected. It is often possible to detect water intrusion into the composite.

A new generation of x-ray inspection systems, based on a concept called reverse geometry, should prove useful for all composites. This real-time radioscopy system has produced results from composite materials showing improved sensitivity and resolution. An effort is currently being made to develop a portable unit for use in the field in addition to the currently available laboratory systems.

Neutrons

While x-rays are attenuated as a linear function of the density of the materials through which they pass, the attenuation of neutrons shows a generally random pattern when compared to the atomic weight of the material. There is a high

neutron attenuation for several light materials, hydrogen, boron, and lithium in particular, and relatively low attenuation for most metals.

For composite structures, the high sensitivity of neutrons to hydrogen means that neutron radiography can display images of adhesive, water, corrosion. An additional application may be found in detecting variations in organic matrix materials.

Most neutron radiographs are produced using a nuclear reactor as the radiation source, very much limiting the utility of this method. Advances in transportable neutron sources have been made, including source systems for depot and field applications. These typically require much more time to produce an acceptable image than reactor-based systems.

X-ray Backscatter Imaging

Conventional radiographic inspections rely on the attenuation of a beam of penetrating radiation through an object to form an image of that object (the so-called shadowgraph). At the low x-ray energies normally used with composites a large portion of the attenuation is due to scattering. This suggests the use of scattered radiation to analyze the inspected object.

Systems have been developed for backscatter imaging. The backscatter intensity, as a function of source and detector position and geometry, contains information about the material properties. Indications from density changes associated with voids, foreign material inclusions, cracks, etc. may be found. This inspection tool is especially useful for the inspection of laminated structures, where tight delaminations, with gaps of less than 50 micrometers in width, can be detected.

The x-ray backscatter signal contains quantitative information about variations in density and the location of the variation within the depth of the material. These characteristics, coupled with the single-sided inspection approach, present advantages for the inspection of composite structures.

Computed Tomography

Computed tomographic inspection, developed and popularized in the medical industry, is being used more and more for composite inspection. The resulting image looks like a slice taken across the inspected object. This has shown to be a powerful tool when inspecting complicated multi-layer multi-component composites.

One important advantage of tomography is the extremely good contrast sensitivity; variation less than 0.1 % are detectable. Additionally, whereas conventional radiography produces a two-dimensional representation of the object, tomography retains the three-dimensional nature of the image.

The necessary trade off when using this technique is that the times required to perform an inspection are relatively long and the equipment is quite costly.

All radiography/radioscopy technologies except for x-ray backscatter are mature. They may be used in all aspects of process inspection and control if the images produced are digital and can be provided in real-time or near real-time. X-ray backscatter should be considered a developing technology. It could be applied to the CAV program in as little as one year with sufficient development support.

Resonance or Mechanical Impedance

This one-sided inspection method detects laminar discontinuities within composites by setting up a continuous sonic wave within the material and sensing the mechanical stiffness (impedance) of the material. For example, a delamination or disbond reduces the normal surface stiffness. Flaw indications can be seen as a phase, amplitude, or resonant frequency shift in the sonic energy. This method is particularly useful in complex bonded structures where access limitations restrict the use of UT through-transmission.

This technology is developing. It is expected to take several years (1 to 3 years) of effort for full maturity. When fully developed, it could be used primarily in end of process and in-process inspection .

Tap Test

The tap test, using either a coin or special impact hammer, continues to be commonly used for in-service inspection despite the availability of more sophisticated less subjective inspection tools. It is especially useful for flaws that are fairly large and close to the surface.

It is sensitive only to defects such as delaminations or unbonds and relies on the different acoustic resonance of the loose upper layer compared to the surrounding material. This methods suffers from subjective interpretation, declining sensitivity with flaw depth, and an inability to calibrate effectively for either flaw size or depth.

Several attempts have been made to instrument the tap test by incorporating machine-based tappers and signal processing equipment. The results have not made a significant impact on composite inspection applications.

Tap testing is a mature technology; it could be used primarily in end of process and in-process inspection .

Ultrasonic Through-transmission Testing

Ultrasonic testing (UT) makes use of high frequency mechanical vibrations. For composite materials, frequencies are typically in the megahertz range.

Composite materials offer special challenges to UT inspection. Because the materials are highly attenuating, multi-layered, and anisotropic, it is often difficult to transmit and receive the necessary sonic signals which contain UT information. Large reflections are produced when ultrasound is directed from one medium to another with a very different acoustic impedance. Furthermore, sonic energy can be channeled or directed along preferential directions (not necessary those useful in the inspection) in laminate and filament wound structures.

The ultrasonic inspection geometry can be either through-transmission (transmitter and receiver on opposite sides of the structure) or one-side pulse-echo (transmitter and receiver on the same side of the structure).

In through-transmission inspection, the signal strength of a pulse of ultrasonic energy transmitted through the material is measured. Locations where there is a delamination, void, or inclusion, for example, will show a reduced received ultrasonic intensity.

This test approach is the most commonly used production and/or in-process control inspection for composite materials. It is moderately easy to automate, provides essentially constant sensitivity to flaws regardless of their depth within the structure, and is fairly easy to interpret. The method is sensitive to most flaws that are planer in nature and lie roughly parallel to the surface; this describes most of the common flaw types found in layered composite structures.

Generally, this method requires access to both sides of the structure. This often reduces the usefulness of this approach for in-service inspection. Furthermore, the speed and data recording advantages of automated systems are usually not available for field inspection. With these comments in mind, it must be noted that more automated field units are being developed.

Through-transmission, as well as pulse-echo and pitch-catch, ultrasonics are mature technologies. They may be used in all aspects of process inspection and control if the images produced are digital and can be provided in real-time or near real-time.

Ultrasonic Pulse-echo Testing

This inspection approach requires access to only one side of the composite structure. Indications of flaws are detected by measuring the time of arrival and/or the signal strength of sonic echoes. For example, delaminations cause the returning echo to arrive earlier than would be expected from the travel time required for the

back surface. This method is commonly used in field applications since the single transducer/receiver makes it simpler to apply in a manual test.

An advantage of the pulse-echo systems is that flaws of different depths can be distinguished from one another using geometry and time-based considerations. The pulse-echo method is also advantageous in that it offers increased sensitivity to foreign material inclusions often associated with the manufacturing process for sandwich composites. Many expendable paper and plastic materials are used in handling and transporting raw materials. These have often found their way into the composite laminates and have been cured in place. Often not observable in through-transmission measurements, most of these inclusions offer a reflected signal sufficient to be detected by pulse-echo ultrasonics.

Ultrasonic Pitch-catch Testing

This inspection technique makes use of separated transmitters and receivers to detect flaws. The angle orientation frequently allows measurements of flaws associated with a particular ply orientation. In addition to characterizing matrix cracking, it is also sensitive to linear voids or porosity. It has also been used to characterize the various levels of impact damage. In operation it is similar to pulse-echo, however, with large angles between the transmitter and receiver the increased path length can seriously reduce signal strengths.

Visual Inspection

Many composite structures are not transparent or translucent so that visual inspection is often reduced to exposed surfaces. Observable defects are normally limited to surface cracks, holes or voids, inclusions, porosity, disbonds at joined parts, and impact damage. Visual aids, such as high intensity light sources, magnifiers, bore scopes, and television cameras, can be used to enhance the detectability of surface related defects.

Many of the more severe defect conditions are visually detected. Punctures, surface-ply delamination, scratches, gouges, and heat damage can often be detected. Disbonds between the surface skin and substructure core can sometimes be detected as a blister in the skin or an edge separation.

One visual inspection approach, to detect impact damage, is to paint the composite surface with a paint containing micro encapsulated dye. When crushed by an impact, the dye is released and reveals the location of the impact. Another possible indication comes from stress whitening in glass reinforced plastic, which results in a loss of optical transparency, and may result from resin-fiber disbonding or resin cracking.

It must be cautioned that very significant impact damage may occur in subsurface layers that may not be shown at all in the exposed surface layers. Typical surface indications may outline suspicious areas for further inspection so that the extent of impact damage can be determined.

Visual inspection is a mature technology. It may be used in all aspects of process inspection and control if the images produced are digital and can be provided in real-time or near real-time.

Other Techniques

Several additional NDE technologies have been used in the field of composites which might prove useful in the inspection of simple to complex structures. Additionally, methods are continuously being developed and some may have missed the attention of the author. Although in most cases those listed below are not as well developed as the methods discussed above (and are considered as laboratory technologies), they are included in an attempt to cover the topics as completely as possible. In all cases, several years of additional development would be required for maturity. They include:

Electromagnetic Acoustic Transducer (EMAT) – used as a ultrasonic receiver. The inspected material must be an electrical conductor.

Flying Spot IR Camera – a variation on IR thermography.

Laser Doppler Vibrometry – an improved approach to laser optical interference patterns.

NMR Imaging – useful in detecting water or other liquid incursion.

Scanning Photo-acoustical Microscopy – a sophisticated variation of thermal imaging. May have a good application in large area studies.

Tagged Materials – very fine magnetic, magneto restrictive, piezoelectric, and/or acoustic material particles are uniformly introduced into the matrix and/or fibers. Flaws that may be detected include: voids, porosity, cracks, foreign material inclusions, cure state, impact damage, disbonds, variations in thickness, and fiber misalignment. Sensing may be active or passive.

Vibrothermography – the structure is vibrated at low amplitudes and localized heating is generated at defects such as delaminations, large matrix cracks, broken fibers, etc. Real-time thermography is used to record the resulting heat patterns. This method has limited applications because of the method of introducing energy into the inspected part.

The concept of NDE sensor systems embedded within composites is becoming more and more popular. These sensors may serve as detectors for many of the NDE methods described above. Some discussion of embedded sensors may be found in Section 6 and 7 and in Appendix A.

6. FUTURE DIRECTIONS

As stated above, there are several categories of implementation/development of NDE technologies that may have CAV applications. Some may be used essentially"off the shelf", while others may require a small additional effort to modify them for CAV usage. Others would require many years of concentrated effort to move from the laboratory to the manufacturing shop floor or for use in the field. The following compilation is intended to review these categories.

a) Methods in use requiring little additional development and/or modification

These include: acousto-ultrasonics, infrared thermography, laser holography (and other optical inference methods), liquid penetrants, radiography/radioscopy, tap testing, all aspect of conventional ultrasonics, and visual inspection.

b) Methods in the laboratory or with limited use which require further development

These include: eddy current inspection, microwave NDE, nuclear magnetic resonance imagine, resonance or mechanical impedance, scanning photo-acoustic microscopy, x-ray backscatter, tagged materials, and vibrothermography. Some of these could be available to the CAV program in as little one year with proper development support. The majority would require 3 to 5 years of concentrated effort to become fully mature.

c) Advanced concepts that may be viable for CAV

These are methods that are being considered and/or in the first stages of development. They include: non-contact ultrasonics such as air coupled UT and/or laser UT, improved large area IR arrays, electromagnetic acoustic transducers, smart materials and micro-activators, and embedded sensors of all types (including the SMARTWEAVE concept). These could be available in 1 to 5 years of concentrated effort.

d) Recommendations for future support

Without additional details concerning the design concept and selection of materials it is difficult to make exact recommendations for future NDE technology support. The following is an attempt to identify those methods which would have a high probability of successful development if funding support could be found for a dedicated development effort.

Several technologies that could be developed for CAV can be used with any type of composite material. These include:

reverse geometry x-ray radioscopy (especially development of field units and embedded imagers)

advanced signal processors and thermal sources for IR thermography, in-field systems

improved resolution and rapid large area scan capabilities for backscatter x-ray radioscopy

large area two-dimensional ultrasonics for rapid scanning, high power ultrasonics transducers for improved penetration in thick section materials, advanced ultrasonic in-field systems

further development of tagged materials

use of embedded sensors for process inspection/control and continued state-of-health monitoring from cradle to grave

One additional method recommended for additional future development is useful only with conducting composites (for example, graphite/epoxy). It is:

advanced eddy current methods

Finally, one method for serious consideration operates effective only with non-conducting materials (such as glass fiber reinforced plastic). This is:

all aspects of microwave NDE

7. CONCLUSIONS

When engineering details such as design concepts and materials recommended for this program are available, it will then be possible to select a number (perhaps only a few) nondestructive methods from those discussed above for inspection purposes. At this time, the following general comments can be made.

The overall summary of inspection techniques as related to composite structures includes many diverse yet complementary methods. These should be capable of inspections for all critical flows. The information contained in Appendix B provides a means of initial sorting for the selection of inspection methods for particular discontinuities.

It is concluded that the NDE methods that are currently most widely used in industry for composite inspection are ultrasonics and radiography. Using these methods, many different types of defects and flaws can be detected and characterized. Complimentary methods, IR thermography and holography have the attraction of being single sided non-contact and able to inspect large areas in short periods of time. Advances in digital signal processing have provided important enhancements to both methods. New methods include eddy current, x-ray backscatter, acousto-ultrasonics, and microwave NDE.

When investigating appropriate NDE technologies, an important material and function related consideration must be addressed. The radiation source associated with the method or methods must be compatible with <u>all</u> of the materials being inspected or able to be seen by the inspection energy source. For example, one must assess the sensitivity of materials to x-rays, microwaves, thermal shock, energy couplants (in the case of ultrasonics), laser light, etc. Consideration must be made both to the major structure and to any additional sensitive components which may be enclosed and/or embedded within the structure.

Specific recommendations for CAV ATD nondestructive evaluation methods are difficult to develop at this time. Enough is known, however, to make several important recommendations concerning the way nondestructive testing may be used in this program.

A consideration of highest importance is that of concurrent engineering; the engineering approach should be one of <u>designing for nondestructive testability</u>. This means that nondestructive evaluation should be considered from the very beginning and throughout the concept and design process. The importance of nondestructive evaluation is well understood; the ability of achieving it throughout the life of the vehicle will be greatly simplified if NDE functions are held to the same high priorities as other engineering standards.

As critical as building NDE into the program from the beginning, the question of where and when nondestructive evaluation is applied is also very

important. It is recommended that nondestructive evaluation should be a cradle to grave function. Therefore, it is important to reconsider the role that NDE is playing in manufacturing and fabrication is changing.

In the past, NDE has played a traditional role primarily as a quality control function. As described above, this is usually called end of process inspection. Obviously, when the quality of the tested object does not meet standards, it must be rejected and either re-worked or scrapped. Both re-work and scrap represent an unnecessary waste of time and resources. A far better approach is known as in-process inspection. The end result of this advanced effort is that waste associated with re-work and scrap is significantly reduced and production efficiency in greatly increased. The most advanced approach is known as in-process control. Here, using the same types of NDE technology described above, the NDE sensor signals are used to control the manufacturing. These systems are currently being developed with very successful results in reduction of waste and re-work.

It is highly recommended that the CAV ATD composite fabrication process employ, at least, the <u>in-process inspection</u> scheme. One must consider the economies based on the number of composite assemblies to be manufactured (for the CAV ATD program probably very few) before a recommendation of full in-process control could be made. That approach would ensure production of the highest quality parts, however, it is the most expensive to implement.

If the recommendation made in Section 2 for nondestructive testing from cradle to grave is followed, it will require that concentration be placed on the development of field inspection systems to evaluate in-service damage. Some technologies adapt themselves to field applications better than others. These are normally the non-contact methods, such as visual inspections, x-ray radiography, IR thermography, laser interference methods, and microwave NDE. This does not eliminate field applications of others such as ultrasonics. Of course, the simple methods such as tap testing and visual inspection can be used nearly as easily in the field as on the manufacturing floor.

Current trends in NDE development are towards large area or large field of view inspection systems. These are typically computer-controlled robotics devices used to inspect large areas in a short time; these systems could play an important role in CAV ATD composite inspection. In addition to controlling the robot which moves the radiation source and detector, the multi-task computer has advanced signal processing capabilities. While these systems are most commonly found in the manufacturing area, efforts are being made to develop depot level and/or transportable field units.

An additional area to investigate when finally selecting appropriate NDE technologies is the increasingly popular use of embedded NDE sensors. These sensors and detectors may be of assistance in a wide variety of manufacturing and condition monitoring functions. They are often used in the cradle to grave approach. For

example, optical fiber arrays, where the fibers are coated with appropriate coatings, are embedded within composite structures. These may then be used to assess cure state during manufacture and later used to assess moisture incursion, impact damage, and structural state-of-health. Another example of embedded sensors is to be found in the SMARTWEAVE program described in Appendix A.

Finally, nondestructive evaluation of these already complex laminate materials may be further complicated with the addition of other layers yet to be identified and discussed. These would include any protective or preservative materials intended to reduce water intrusion, improve abrasive resistance, or simply for cosmetic appearance. Additionally, layers associated with armor and/or with low observable properties and/or signature control could further complicate nondestructive evaluation. Until these materials are identified and fully described, it is impossible to completely understand how the additional surfaces may interact with the penetrating radiation (electromagnetic, sonic, thermal, etc.). On the positive side, a great deal of effort has been made in the development of NDE techniques for low observable materials and signature control coatings. This information is classified and outside of the scope of this study, however, it is accessible if required.

In summary, the capabilities of nondestructive evaluation, used both in identifying defects and flaws in composite structures and controlling the quality of their manufacture, continue to expand. With ongoing developments in instrumentation, automation, and signal processing technology, NDE will continue an enhanced role not only as a flaw detector but also as an effective tool for process control and waste minimization earlier in composite fabrication processes.

Acknowledgments

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APPENDIX A

DIRECT CONTACTS MADE TO DISCUSS THE CAV ATD PROGRAM

This appendix contains a summary of contacts made during the Phase I Study for the CAV ATD Project. The institutions (agencies, companies, etc.) are listed in alphabetical order. Each entry contains the name of the institution, institution address, point of contact, telephone and FAX numbers, date visited and/or contacted, and a brief summary of program highlights. This appendix does not contain any information on institutions which, when contacted, provided little or no meaningful information for the project.

Institution: Aberdeen Proving Grounds
Systems Test Activity

Address: NDT Branch
Aberdeen Proving Grounds
Aberdeen, MD

Point of Contact: Mr. Jim Faller

Telephone Number: (410) 278-4461

FAX Number:

Date Visited: 9 September 1993 and prior (telephone contact only)

Program Highlights: The in-house NDE facilities are primarily focused on high energy x-ray radiography and radioscopy(of little use for CAV) and older ultrasonics equipment with little capability for scanning and/or signal processing. Mr. Faller has a great deal of experience in materials analysis and he would like to participate in the CAV program.

Institution: Advanced Research Projects Agency (ARPA)

Address: 3701 North Fairfax Drive
Arlington, VA 22203-1714

Point of Contact: Mr. Len Ogborn

Telephone Number: (703) 696-2340

FAX Number:

Date Visited: 12 July 1993 (telephone contact only)

Program Highlights: Mr. Ogborn is involved with the ARPA Light Contingency Vehicle (LCV) Program. When he was contacted to inquire whether there was any information available, Mr. Ogborn indicated that it is much too early in this program to be able to provide any meaningful information for CAV. However, he would like very much to receive information about the CAV program.

Institution: Aerospace Corporation

Address: M2/248
P O Box 92957
Los Angeles, CA 90009

Point of Contact: Dr. Gary F. Hawkins, NDE Scientist

Telephone Number:

FAX Number:

Date Visited: 26 April 1993 (contacted at JANNAF Conference)

Program Highlights: This group consults for the Air Force, primarily on applications of thick section composites applied to rocket motor cases and associated rocket NDE methods. They use a very general approach, selecting from a variety of methods depending on the specific problem. Some laboratory equipment is available. However, they also perform work at Air Force and contractors laboratories.

Institution: AJM Electronics, Instrumentation Division

Address: 619 North First Street
San Jose, CA 95112

Point of Contact: Mr. Robert A. Macy, President

Telephone Number: (408) 286-3985

FAX Number: (408) 286-9121

Date Visited: 12 August 1993

Program Highlights: Discussions were held on a new break-through eddy current device. This NDE technique requires that the inspected material must be conducting, such as graphite/epoxy. The new method has superior penetration for thick sections and may prove especially useful for impact damage assessment for broken fibers. The method will be evaluated using thick section composite standard materials.

Institution: American Research Corporation of Virginia

Address: 642 First Street
P O Box 3406
Radford, VA 24143-3406

Point of Contact: Dr. Russell J. Churchill, President

Telephone Number: (703) 731-0655

FAX Number:

Date Visited: 4 August during Progress in QNDE Conference and 17 August 1993 and following (other than contact at QNDE Conference only by telephone)

Program Highlights: This group has limited work on composites; the most interesting applications appear to be using IR thermography and microwave applications. They are a possible source for laboratory work in microwave applications.

Institution:	Army Research Laboratory
Address:	U. S. Army Materiel Command Army Research Laboratory Materials Directorate AMSRL-MA-CB 405 Arsenal Street Watertown, MA 02172-0001
Point of Contact:	Mr. Walter Roy, Branch Chief Materials Evaluation Ms. Lisa Tardiff, Quality Assurance Specialist Materials Evaluation
Telephone Number:	(Roy) (617) 923-5285 (Tardiff) (617) 923-5552
FAX Number:	(Roy) (617) 923-5243 (Tardiff) (617) 923-5477
Date Visited:	14-15 June 1993

Program Highlights: This group is developing NDE techniques for applications to thick composites. Major inspection tools are x-ray radiography and immersion ultrasonics. They have developed a set of well characterized standard materials for assessment of various NDE methods. They are also trying to develop a portable UT unit for field applications. Efforts are being made to further develop and enhance a software system for NDE image evaluation called Image System Inspection Software (ISIS). The group also contributes to the SMARTWEAVE project which is expected to be used for in-process control in resin transfer molding applications. In the SMARTWEAVE system, some glass fibers are replaced with carbon fibers. The resulting orthogonal conducting array can be used to measure critical process control parameters, such as the motion of the resin front during injection and resin cure state. After manufacture the same sensor array can be used to measure impact damage and other vehicle state of health assessments. Some members of this group have been or are being transferred to the NASA Langley site.

Institution:	Army Research Laboratory Composites Development Branch
Address:	Materials Directorate Arsenal Street AMSRL-MA-PA Watertown, MA 02172
Point of Contact:	Mr. William E. Haskell III, Senior Materials Engineer Mr. Dana M. Granville, Materials Engineer
Telephone Number:	(617) 923-5172
FAX Number:	(617) 923-5154
Date Visited:	15 June 1993

Program Highlights: These engineers have been involved with composite vehicles for some time, including the Composite Infantry Fighting Vehicle manufactured in cooperation with FMC. They are also involved with the SMARTWEAVE program. They passed along a great deal of information on composite vehicle manufacture experience and the use of thick composites. This group has studied fire/smoke tests on composite vehicle applications. This appears to be an important resource available to the CAV program.

Institution: Army Research Laboratory
Composites Development Division

Address: Materials Directorate
Arsenal Street
AMSRL-MA-PA
Watertown, MA 02172

Point of Contact: Mr. Richard J. Shuford, Group Leader
Materials Research Engineer

Telephone Number: (617) 923-5572

FAX Number:

Date Visited: 15 June 1993

Program Highlights: Mr. Shuford described research being done at Watertown on composite manufacturing. These include a SBIR project intended to measure the environmental effects of pre-preg materials. They are also investigating the use of IR thermography as a NDE tool and also as a method of assessing the cure state by measuring the exotherm energy. Work on IR thermography is also being done at Watertown.

Institution:	Center for Composite Materials University of Delaware
Address:	Composites Manufacturing Science Laboratory University of Delaware Newark, DE 19716-3144
Point of Contact:	Dr. John W. Gillespie, Professor and Assoc. Director Mr. Karl V. Steiner, Asst. Director
Telephone Number:	(Gillespie) (302) 831-8702 (Steiner) (302) 831-6703
FAX Number:	(Gillespie) (302) 831-8525 (Steiner) (302) 831-8525
Date Visited:	8 July 1993

Program Highlights: The Center for Composite Materials has strong ties to the Army Research Office through the University Research Initiative Program. Special areas of interest to the CAV program are in the integration of NDE inspection and in-process control. This center contains laboratories and workshops which cover all aspects of composite manufacture including computer controlled weaving machines, full materials testing and characterization laboratories, up to date manufacturing facilities, and off line NDE (mostly ultrasonic-based) as well as in-process NDE-based control of manufacturing. For an example of the latter, they have developed a multi-parameter in-process control system for mandrel wound ply placement. This is one of very few operating systems in existence. Two publications contain detailed reviews of the program; they are the *Annual Report and Overview of the University of Delaware Center for Composite Materials*. This is one of the best equipped and coordinated centers that was visited during this project. The CAV program should be able to make good use of a continued close association with this center.

Institution: Army Research Laboratory

Address: Vehicle Structures Directorate
NASA Langley Research Center
M/S 266
Hampton, VA 23681-0001

Point of Contact: Dr. Felton D. Bartlett, Jr.
Chief, Structural Mechanics Division

Telephone Number: (804) 864-3952

FAX Number: (804) 864-3970

Date Visited: 25 May 1993

Program Highlights: Discussions with Mr. "Bart" Bartlett during visit at NASA Langley NDE Center disclosed that he is very supportive of the CAV project and would like to involve those Army Research Laboratory personnel that have transferred from Watertown to Langley in the experimental NDE portion of this project. Recommended that he be included in the distribution list for the Final Report for Phase I.

Institution:	Center for Nondestructive Evaluation (Center for NDE) Iowa State University
Address:	1915 Scholl Road Iowa State University Ames, IA 50011
Point of Contact:	Dr. David K. Hsu, Senior Scientist, CNDE Dr. Vinay Dayal, Asst. Professor, Aerospace Engineering and Engineering Mechanics Dr. Daniel O'Hare Adams, Asst. Professor, Aerospace Engineering and Engineering Mechanics
Telephone Number:	(Hsu) (515) 294-2501 (Dayal) (515) 294-0720 (Adams) (515) 294-3039
FAX Number:	(Hsu) (515) 294-7771 (Dayal) (515) 294- (Adams) (515) 294-8584
Date Visited:	16 June 1993

Program Highlights: Most of the experience within this group has been gained from working on proposed Navy composite submarine applications. They had a subcontract from University of Illinois for this effort which was completed in 1991. Most NDE applications have been focused on ultrasonics. There is good collaboration between NDE scientists and materials engineers, especially in trying to understand the failure of materials and how NDE may be used for failure prediction. Direct efforts on thick composite materials is rather limited at this time, however, the Center for NDE has a great depth of experience that might be used on composite inspection problems in the future.

Institution:	Center for Nondestructive Evaluation (CNDE) Johns Hopkins University
Address:	CNDE Maryland Hall The Johns Hopkins University Baltimore, MD 21218
Point of Contact:	Professor Robert E. Green, Jr. Director
Telephone Number:	(410) 516-6114
FAX Number:	(415) 516-5293
Date Visited:	9 July 1993

Program Highlights: When compared to the Center for NDE at Iowa State University, this Center remains very active in the NDE of composite research. Thick section work has been focused on submarine and rocket motor case applications. Major areas of NDE emphasis include: ultrasonics, acousto-ultrasonics, laser ultrasonics, acoustic emission, laser speckle and holography, x-ray radioscopy and radiography, infrared thermography and imaging, thermal wave imaging, magnetic resonance imaging, and laser-based interferometric strain/displacement systems. This center is making rapid advancements in laser-based NDE technologies. In addition to NDE research laboratories there are fully developed material testing facilities for fatigue, fracture, corrosion, surface analysis, microsample testing, and structural testing. The U S Army Research Laboratory (formerly Army Materials Technology Laboratory) is a sponsoring member of the CNDE. Complete details of this program are found in their *Annual Report*.

Institution:	Center of Excellence for Composites Manufacture GreatLakes Composites Consortium
Address:	8400 LakeView Parkway Kenosha, WI 53142-7403
Point of Contact:	Mr. Martin G. Bradley Program Manager
Telephone Number:	(414) 947-8914
FAX Number:	(414) 947-8919
Date Visited:	23 June 1993

Program Highlights: This group manages the Navy Center for Excellence for Composite Manufacturing Technology. The consortium is composed of approximately 70 industrial companies and academic institutions. They have the capability, through consortium members and in-house facilities, to design, test, and manufacture components on a small scale. At this time they have no in-house NDE capabilities. Several projects may be of interest to the CAV program: development of composites with high thermal conductivity fibers and development of resin transfer molding of equipment racks with special regard to heat dissipation and EMI shielding. Additional information of interest is contained in the report *Shipbuilding Composites Manufacturing Technology Plan.*

Institution: Digiray Corporation

Address: 2239 Omega Road
San Ramon, CA 94583

Point of Contact: Dr. Richard D. Albert, President

Dr. Thomas M. Albert, Marketing Director

Telephone Number: (510) 838-1510

FAX Number: (510) 838-1968

Date Visited: 13 August 1993

Program Highlights: This company has pioneered a new x-ray radioscopy technique called reverse geometry x-ray radioscopy. They have shown experimental results indicating improved sensitivity and resolution compared to film and other radioscopy systems. Efforts are being made to development a portable system for field applications. Sensors are of the size and materials such that they may possibly be embedded within thick sections for in-field damage assessment. This method will be tested with thick section composite standard materials.

Institution: Failure Analysis Associates, Inc.

Address: 8411 154th Avenue, NE
Redmond, WA 98052

Point of Contact: Mr. Tim Herrington, Senior Engineer

Telephone Number: (206) 881-1807

FAX Number: (206) 885-9628

Date Visited: 17 August (telephone contact only)

Program Highlights: This company has developed a large area (approximately one foot square) two-dimension ultrasonics array and associated electronics for pulsing and signal processing. This was originally intended for use with thin section aircraft composites. They have been given a contract from TACOM for further development of this technology for the CAV. The equipment would allow much faster scanning rates for inspecting large areas of composite. The method will be tested using thick section composite standard samples.

Institution: FMC Ground Systems Division

Address: 1205 Coleman Avenue
Santa Clara, CA 95050

Point of Contact: Mr. Paul Para
Manager, Composite Structures

Telephone Number: (408) 289-4996

FAX Number: (408) 289-4853

Date Visited: 12 August 1993

Program Highlights: This meeting was intended as a briefing so that FMC could have a more complete understanding of the NTIAC project and could then request additional help if needed. A review of their design approach indicated that a thick section hull, using glass reinforced plastic, is being considered. Mr. Para described the Composite Infantry Fighting Vehicle and the use of ultrasonics as an inspection tool for this program. He also discussed the possibility of multi-layered materials used in the CAV hull; these could include integrated armor and signature control materials. Armor could also be added to the hull (multi-layers and armor are not considered in the NTIAC project).

Institution: General Dynamics Land Systems (GDLS) Division

Address: P O Box 2094
Warren, MI 48090-2094

Point of Contact: Ms. Susanne M. Dolecki, Senior Engineer
Composites Technology

Telephone Number: (313) 825-8843

FAX Number: (313) 825-8660

Date Visited: 27 July 1993

Program Highlights: This meeting was intended as a briefing so that GDLS could have a more complete understanding of the NTIAC project and could then request additional help if needed. A review of their design approach indicated that a "space frame" hull, using graphite/epoxy members, is being considered. Armor would be added to the hull (armor is not considered in the NTIAC project). Most hull components would be thin section, of the order of 1/4 inch or less. This approach would present a number of serious challenges for NDE inspection.

Institution: Industrial Quality Inc. (IQI)

Address: 640 East Diamond Avenue
Suite C
Gaithersburg, MD 20877

Point of Contact: Mr. Harold Berger, President
Dr. Eric A. Lindgren, Materials Scientist

Telephone Number: (301) 948-2460

FAX Number: (301) 948-9037

Date Visited: 6 July 1993

Program Highlights: Primary projects include infrared thermography, both through-transmission and reflected, and back scatter x-ray radiography. This group has a strong background in thermography signal processing. They have worked on thick section composites for the Coast Guard R&D Center through SBIR Phase I project; this included impact damage. They claim that they can see defects with IR thermography as others can see with ultrasonics with equal sensitivity and resolution.

Institution: Jet Propulsion Laboratory
California Institute of Technology

Address: Building 125/112
4800 Oak Grove Drive
Pasadena, CA 911109-8099

Point of Contact: Dr. Yoseph Bar-Cohen

Telephone Number: (818) 354-2610

FAX Number: (818) 393-5011

Date Visited: 3 August 1993 at Progress in QNDE Conference and 17 August 1993 (originally scheduled but telephone contact only accomplished because of schedule conflict)

Program Highlights: Dr. Bar-Cohen has worked extensively in ultrasonics inspection of composites. He has worked with Dr. Mal at UCLA and Mr. Owens at Northrop. During telephone conversations he discussed the use of embedded optic fibers covered with PZT material that may be used in a acoustic emission type approach.

Institution: NASA Langley

Address: NASA Langley Research Center
Hampton, VA 23681-0001

Point of Contact: Dr. Eric Madaras
Deputy Director, NDE Science Branch

Telephone Number: (804) 864-4993

FAX Number: (804) 864-4914

Date Visited: 25 May 1994

Program Highlights: This center is composed of the following groups: Thermal, Ultrasonics, Optics, Modeling and Radiography, Microstructure, Instrumentation, and Electromagnetics. Some groups have had considerable experience with thick composites, however, this has been gained primarily on thick section rocket motor cases. In many instances the experience may be directly transferred to CAV type structures. There are many examples of inspections of complex structures. The philosophy of this laboratory places great emphasis on quantitative nondestructive evaluation. A great deal of effort is made to understand the science involved with NDE and to use modeling as an important tool in NDE applications. Examples of NDE methods with possible applications to CAV include: IR thermography for impact damage inspection, phase insensitive array ultrasonics, high temperature ultrasonics for measuring cure state, reverse geometry x-ray radioscopy development, fiber optic sensors, eddy current, development, etc. A comprehensive compilation of laboratory results is contained in *Nondestructive Measurement Science at NASA Langley, Advancing the State-of-the-Art Providing a Quantitative Science Base and Technology Transfer fro Materials/Structures Characterization.*

Institution:	Naval Surface Weapons Center, Carderock Division	
Address:	NSWC Carderock Division Annapolis Detachment Welding Technology, Code 615 Annapolis, MD 21402-5067	
Point of Contact:	Mr. John DeLoach, Jr., Material Engineer Ms. Carol Lebowitz, Material Engineer	
Telephone Number:	(DeLoach) (Lebowitz)	(410) 267-5207 (410) 267-3574
FAX Number:	(DeLoach) (Lebowitz)	(410) 267-3748 (410) 267-3748
Date Visited:	15 July 1993	

Program Highlights: This group is applying NDE to composites although they are in a division where the major emphasis is on welding. In-house applications include x-ray radiography (film) and ultrasonics. There is some thick section experience, however, much of this is based on filament wound cylindrical parts. There is an effort to further develop NDE methods for their particular composite applications.

Institution: Northrop Corporation

Address: 8900 East Washington Boulevard
T242/GK
Pico Rivera, CA 90663737

Point of Contact: Mr. Owen Manning, NDE Engineer

Telephone Number: (310) 942-5263

FAX Number: (310) 9438-8068

Date Visited: 16 August 1993

Program Highlights: This company regularly uses ultrasonics, x-ray radiography, IR thermography, and shearography for in-fabrication inspection of thin section composite parts in the manufacturing area. They also have a great deal of experience in inspecting complex multi-layered composites, mostly gained from the B-2 program. Most of this information is classified, however, it is expected to be declassified within the next year (and accessible now with proper clearance and need to know certification).

Institution: Northwestern University

Address: Evanston, IL
60208

Point of Contact: Dr. Isaac M. Daniel, Professor
McCormick School of Engineering and Applied Science

Dr. Jan D. Achenbach, Professor and Director Center for Quality Engineering and Failure Prevention

Telephone Number: (Daniel) (708) 491-5649
(Achenbach) (708) 491-5527

FAX Number: (Daniel) (708) 491-5227
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Date Visited: 24 June 1993

Program Highlights: Northwestern initiated work for the Air Force on embedded sensors for measuring residual stress in composite curing and water uptake in composites. Work also includes the development of simplified curing techniques for graphite epoxy composites. They use NDE for the study of manufacturing and in-service defects. Their efforts also include NDE applied to the assessment of composite repairs. Major NDE areas of emphasis are: acoustic emission, ultrasonics, x-ray radiography, and laser interferometry.

Institution: Olin Ordnance
Flinchbaugh Operations

Address: 200 High Street
Red Lion, PA 17356

Point of Contact: Mr. Thomas J. Gill, Jr.
Materials Engineer, Composites Structures R&D

Telephone Number: (717) 244-4551

FAX Number: (717) 244-5006

Date Visited: 7 July 1993

Program Highlights: This group has worked for five years to develop a NDE technique for studying a very complex special purpose ordnance component which uses radial ply lay-up laminates. After investigation into the application of a variety of methods, they selected acousto-ultrasonics. The technique requires a special test jig for this specific part; the testing results are very good. This is probably not a useful application for CAV in general, although it may be used in some instances for in-process inspection of some components.

Institution:	University of Akron
Address:	Department of Electrical Engineering College of Engineering Auburn Science and Engineering Center 352b Akron, OH 44325-3904
Point of Contact:	Dr. Nathan Ida, Professor
Telephone Number:	(216) 972-7679
FAX Number:	(216) 972-6487
Date Visited:	1 August 1993 (contact made at QNDE conference)

Program Highlights: Dr. Ida is involved in microwave NDE, including sub-millimeter wavelengths (Dr. Ida has recently published a book on the subject of microwave NDE). He has looked at some composites and would like to inspect thick section composite standard materials. This may be a possible resource for laboratory work with microwave applications.

Institution: Virginia Polytechnic Institute and State University

Address: Center for Composite Materials and Structures
201 Hancock Hall
Blacksburg, VA 24061-0257

Center for Intelligent Material Systems and Structures
Blacksburg, VA 24061-0261

Point of Contact: Professor John Morton, Director
Center for Composite Materials and Structures (CCMS)

Professor Craig A. Rogers, Director
Center for Intelligent Material Systems and Structures (CIMS)

Telephone Number: Morton – (703) 231-6051

Rogers – (703) 231-2900

FAX Number: Morton – (703) 231-9452

Rogers – (703) 231-2903

Date Visited: 26 May 1993

Program Highlights: Both groups have extensive experience in NDE composite applications. CIMS has produced good results from research in health monitoring applied to composite repairs as well as developing NDE techniques for rapid NDE scanning. Further damage assessment work includes introduction of embedded PZT sensors and implementation of mechanical impedance measurements. They also have developed several tagging technologies for adhesives and matrix materials and they are investigating applications of smart composite materials. CCMS has developed vibrothermography and has placed major emphasis on ultrasonics. The center has a full laboratory fabrication facility and they manufacture test samples. Current funding supports research in more than 55 composite-related programs. This program has strong ties with NASA.

APPENDIX B

NONDESTRUCTIVE EVALUATION TECHNOLOGIES MATRIX

The following figure illustrates the various nondestructive evaluation technologies that may be used with thick section composite inspection. The rows list defects and/or flaws that are most often being identified. The column headings indicate the NDE technology used to detect the flaw. These technologies may contain subsets of methodologies that are intended for specific problems. For example, radiography contains several types of energy sources (such as x-ray, gamma ray, neutrons) and computed tomography; optical may include holography, shearography and other interference optical methods; acoustic includes tap test, acoustic emission, acousto-ultrasonics, etc. Details on specific NDE methods is given in Section 5 of the text.

Figure B-1. Major Nondestructive Evaluation Methods and Their Defect Detection Capabilities

	Acoustic	Eddy Current	Microwave	Optical	Penetrant*	Radiography	Thermal	Ultrasonic	Visual*
Breaks**	X	X	X		X	X	X	X	X
Corrosion/Moisture			X	X		X	X	X	X
Cracks**	X	X	X		X	X	X	X	X
Delaminations**	X		X	X	X	X	X	X	X
Disbonds	X			X	X	X	X	X	X
Fiber Misalignment/Breaks		X			X	X			
Foreign Material	X		X			X	X	X	X
Fracture**	X	X	X		X	X	X	X	X
Impact Damage	X	X	X	X	X	X	X	X	X
Porosity	X		X		X	X	X	X	
Thickness/Density Variation	X		X			X		X	
Undercure	X							X	
Voids	X		X		X	X	X	X	

D172.4.1

* defects or flaws on the surface or slightly below and exposed to the surface
** if oriented parallel to the direction of the incident beam

APPENDIX C

BIBLIOGRAPHY

Selected Bibliography

This Appendix contains a selected bibliography intended to list a number of representative publications dealing with the nondestructive evaluation of composites. The focus is on materials suggested by a general understanding of the CAV ATD Program and related to those NDE methods most likely to be used with materials chosen to be used. These papers were selected from those cited in the results of the original bibliographic search performed at the beginning of the Phase I effort (over 350 references cited). Additional documents were found in supplementary research on this topic. Information contained in the Technology Assessment Report was acquired from these documents and from that gained through direct contacts at research institutions. Hardcopies of the papers listed will be kept in the NTIAC files.

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